Time dependency of angular alignment

B.M. Harvey, M. Youngs, A.B. McIntosh, A. Jedele, R. Wada, and S.J. Yennello

In an experiment performed at Texas A&M University's Cyclotron Institute [1,2], a ^{70}Zn projectile beam was impinged on a ^{70}Zn target at 35 MeV/nucleon. During the collision, the projectile nucleus becomes an excited, deformed projectile-like fragment (PLF*). Before the PLF* separates from the target fragment, a low-density region between it and the target can form. This low-density region tends to be neutron-rich due to the action of the asymmetry energy. Part of this neutron-rich region can separate from the target as a relatively neutron-rich portion of the PLF*. The rate at which the nucleons redistribute themselves to reach chemical equilibrium is impactful to studies on the Nuclear Equation of State. This process occurs on the zeptosecond timescale, making it infeasible to take a direct measurement of this rate experimentally. Therefore, these experiments rely on the premise that angular alignment, α, which characterizes how much the PLF* rotates before breaking apart, is correlated linearly with the PLF* lifetime, Δt. The PLF* lifetime is the time that the equilibration process is allowed to continue before the PLF* breaks apart. The work presented here utilizes simulated nuclear collisions, through the Constrained Molecular Dynamics (CoMD) model, to properly characterize and quantify the dependency of α on Δt.

Like the experiment, we focus on the case where the breakup occurs dynamically and the PLF* separates into predominantly two primary fragments, the heaviest fragment (HF) and the lighter fragment (LF). The alignment angle is defined from these fragments' velocity.

$$\alpha = \arccos \frac{\overrightarrow{v_{cm}} \cdot \overrightarrow{v_{rel}}}{|\overrightarrow{v_{cm}}| \cdot |\overrightarrow{v_{rel}}|}$$

$$\overrightarrow{v_{cm}} = \frac{m_{HF}\overrightarrow{v_{HF}} + m_{LF}\overrightarrow{v_{LF}}}{m_{HF} + m_{LF}}$$

$$\overrightarrow{v_{rel}} = \overrightarrow{v_{HF}} - \overrightarrow{v_{LF}}$$

Two methods were used to study the same data set generated from CoMD simulations. The first method, called the Tree Method, was developed to directly track and identify fragments of interest through CoMD events. In particular, this tool was used to identify the PLF* at its time of separation from the target and the subsequent HF and LF when it decays at the time of its breakup. From this data, α and Δt (time from PLF* formation to PLF* breakup) can be found event-wise. The second analysis method implements the experimental assumptions, where the heaviest two fragments found at the end of the event are assumed to be the HF and LF. This analysis method has the same drawback as the actual experiments. In both cases, the PLF* lifetime is not directly measured, but the comparison of the results from both methods gives insight into the details of the dynamics.

Fig. 1 shows the angular distribution for two different collision energies and each analysis method modelled by a 3-term fit, including a sinusoidal statistical peak, a dynamic peak and a correctional flipped peak.

$$Y(\alpha) = A\sin\alpha + BY_{dyn}(\alpha) + CY_{dyn}(180^\circ - \alpha)$$
$$Y_{dyn}(\alpha) = \frac{1}{\sigma^2}\alpha e^{-\frac{\alpha^2}{2\sigma^2}}$$

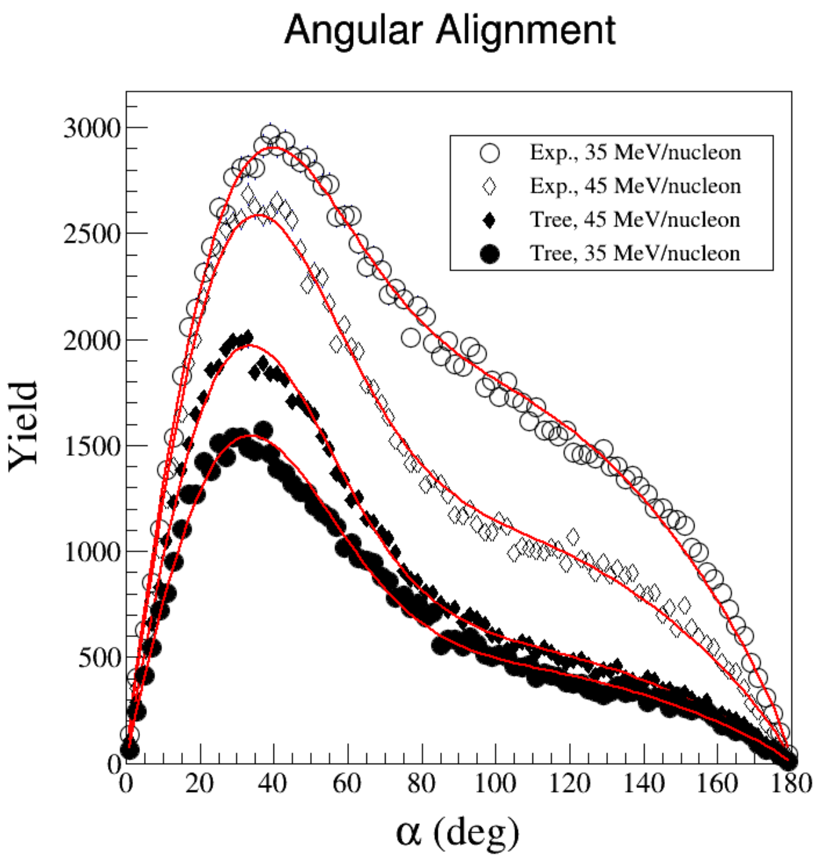

Fig. 1. Angular alignment for 35 and 45 MeV/nucleon simulated collisions utilizing the experimental assumptions (circles) and Tree Method (diamonds).

The model is shown to fit the data well for each distribution and demonstrates that the Tree Method is more selective to the dynamic events we are interested in, especially in the lower energy collisions. This model allows for the extraction of the average alignment angle due to dynamic breakup from the fit parameter, σ, as a function of PLF* lifetime. Fig. 2 shows α versus Δt, as well as the average alignment angle as blue data points, and the average alignment angle in the dynamic peak, $\langle\alpha_{dyn}\rangle$, are shown as black data points for both 35 and 45 MeV/nucleon collisions. The relationship between $\langle\alpha_{dyn}\rangle$ and Δt is explored through a linear fit and for both energies. It was found that $\frac{d\langle\alpha_{dyn}\rangle}{d\Delta t} = 2.0 \pm 0.2\frac{rad}{zs}$, demonstrating a correlation between angular alignment and PLF lifetime in good agreement with the assumptions used in [1,2].

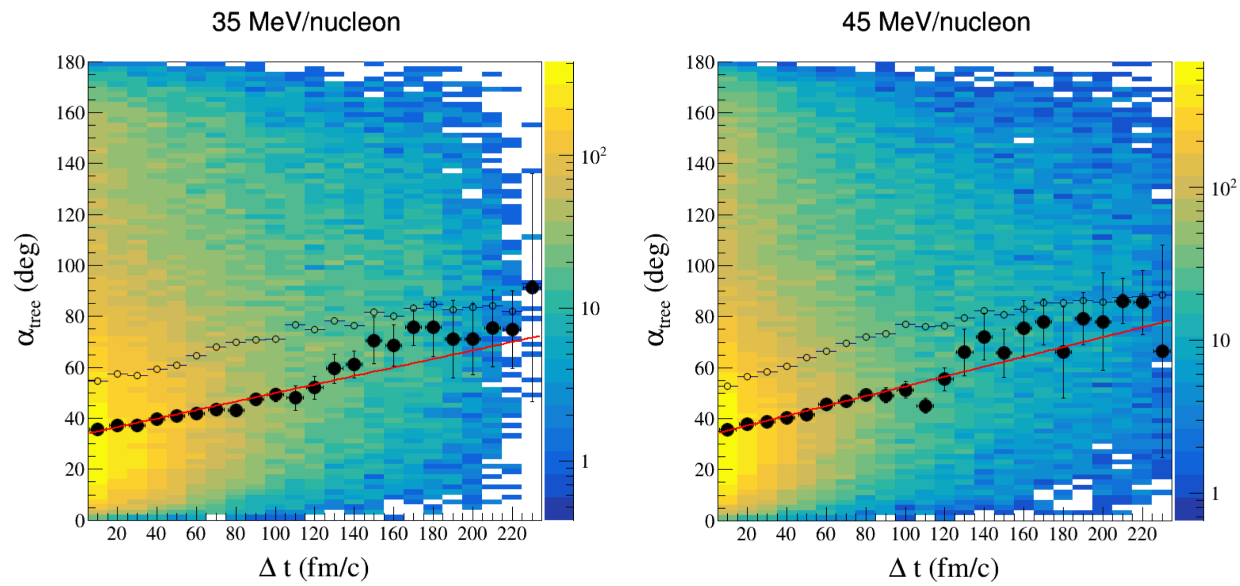

Fig. 2. Angular alignment versus time for 35 (left) and 45 (right) MeV/nucleon collisions utilizing the tree method. The solid data points show how the average alignment angle in the dynamic peak as a function of time, and the open data points represent the average of value in the entire angular alignment distribution as a function of time.

[1] A. Jedele *et al.*, Phys. Rev. Lett. **118**, 062501 (2017).

[2] A. Rodriguez Manso *et al.*, Phys. Rev. C **95**, 044604 (2017).